2 SPACE WEATHER

2.1 Space Weather and Human Technologies

Space weather events have been noted to affect, or even disrupt, human technologies since the development and deployment of the first electrical telegraphs in the 1840s. Electrical currents induced in the Earth by ionosphere and magnetosphere processes caused serious disruptions of telegraphy for decades. Indeed, the great solar storm of 1859 disrupted telegraph operations around the world, causing articles to be published in many major newspapers at that time. Degradation and disruption of wireless signals by space weather effects on the ionosphere have been observed ever since Marconi sent his first transmissions across the Atlantic in December 1901.

Military needs for space situational awareness were evident long before the official beginning of the space age. During World War II, radar signals were a primary element of British defense against the Luftwaffe. Solar radio noise would at times fill the airways, prompting investigations of German jamming capabilities. In fact, particularly severe radar jamming during a large solar event in 1942 led to the discovery of solar radio bursts (only reported following the end of the war). The first measurement of high energy solar cosmic rays was also made during this solar event (by ground-based detectors) and was also reported following the war.

The first transatlantic telephone cable (between Newfoundland and Scotland) was disrupted by the geomagnetic storm of 1958. At the same time, the entire Toronto area lost electrical power because of the storm. Radio communications faltered during that storm in several locations. An Air Force plane loaded with passengers and flying from New Zealand to Antarctica made the 2,000-mile journey without radio contact. The first telecommunications satellite, Telstar 1®, which launched on July 10, 1962, was put out of service after 8 months in orbit by a combination of natural and human-induced radiation in the Van Allen belts. (The Starfish nuclear explosion occurred on July 9, 1962.)

The advent of the space age demonstrated conclusively that ever-advancing technologies—for both civilian and national defense purposes—require an evermore sophisticated understanding of the space environment. Reliable forecasts of changes in this environment—space weather—are now essential for ensuring reliable operations of both space- and ground-based systems. The operations of these systems have often encountered surprises because of solar-terrestrial effects (e.g., Barbieri and Mahmot 2004). Further, "older" problems, such as the disturbance of radar by solar radio noise, require revisiting and reanalysis in the context of newer communications technologies that use different frequencies and implementations than in the past (for instance, the Global Positioning System [GPS] and other positioning, navigation, and timing services; wireless telephony and data transmission services). Contemporary examples of space-weather impacts on many modern technical systems are schematically illustrated in figure 2-1. Details of some of these technological impacts are discussed in side-bar boxes in chapter 3 and at relevant points in the report narrative.

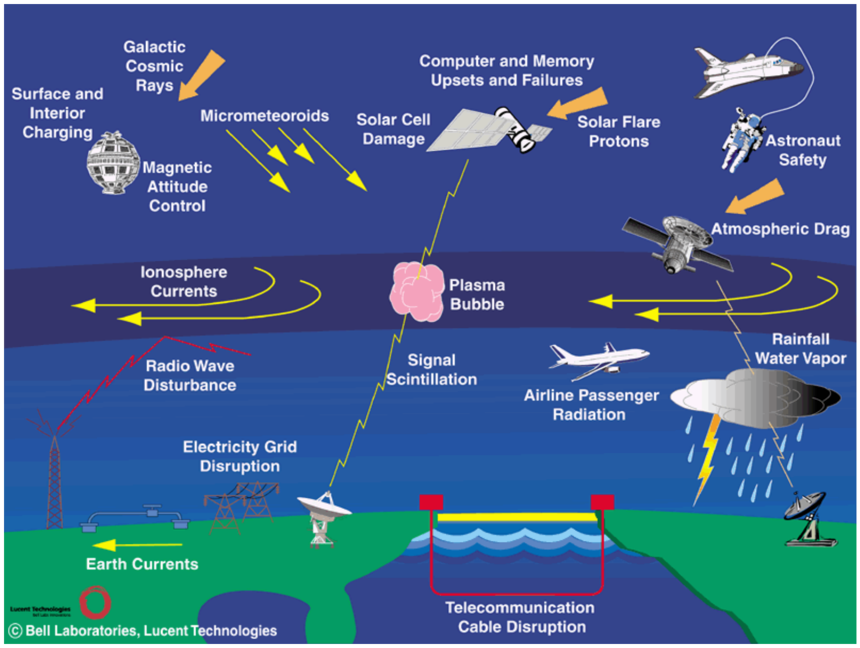

Figure 2-1. Impacts of solar-terrestrial processes on technologies.

2.2 The Emergence of Space Weather Services in the United States

Daily civilian space weather services by the Federal government celebrated their 40th anniversary in 2005, the same year in which the NSWP celebrated its tenth anniversary. The emergence of a coordinated, interagency approach to space weather services and the R&D necessary to support those services began even earlier.

Awareness by civilian agencies of space weather (although not called that at the time) grew considerably at the time of, and following, the International Geophysical Year in 1956-1957. Routine civilian Federal space weather services began a decade later in 1965, the same year that several scientific entities within the Department of Commerce—the Weather Bureau, Central Radio Propagation Laboratory (CRPL), and U.S. Coast and Geodetic Survey—were brought together as the new Environmental Science Services Administration (ESSA), headquartered in Boulder, Colorado. Through several changes in name and organization, a piece of CRPL was transformed into the current Space Environment Center (SEC) within NOAA's National Weather Service (NOAA/NWS). In 2004, the SEC joined the NWS family of prediction centers, known as the National Centers for Environmental Prediction (NCEP).

Space environmental forecasting efforts by NASA and the Air Force began in 1962. DOD's space weather forecasting centers have since migrated from the Air Weather Service to the Air Force Space Command (AFSPC) and then to the Air Force Weather Agency (AFWA). Forecasting research activities began in 1966 at the predecessor to the current Air Force Research Laboratory (AFRL). Currently, the Space Weather Operations Center (SWOC), located at Offutt Air Force Base in Omaha, Nebraska, is a functional element of AFWA.

In the course of assessing successes and achievements during the first 10 years of the NSWP, this report also documents the continued growth in demand for space weather services from both governmental (defense, regulatory, and scientific missions) and civilian interests. Knowledge about the complex system formed by the Sun and the Earth's environment continues to increase, and capabilities for modeling and predicting this dynamic system continue to grow rapidly.

In *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, a survey committee of the National Research Council devoted a chapter to space weather research and its applications (NRC 2002). In discussing the importance of the NSWP, the authoring committee stressed that "*A key function of the National Space Weather Program is to develop processes and policies for monitoring the space weather environment.*" The survey further stated that "technological changes are occurring at a very rapid pace in both large-scale systems and small-scale subsystems that can be affected by solar-terrestrial processes. This is true for both ground- and space-based systems." For example, the electric power grid system in the United State is becoming more interconnected through the use of power-sharing pools and other multi-company arrangements. Due to this interconnectedness, a problem caused by a space weather event in one geographical region of the power grid could potentially cascade to a distant region not directly affected by that event. At the opposite extreme of the size scale, rapid advances continue in microelectronics and in the miniaturization of circuits, Some of these changes can make the components and the systems containing them more vulnerable to effects of space radiation. The increasing use of commercial off-the-shelf components in national security programs (as well as in commercial programs) can also make space subsystems and systems more susceptible to space radiation effects.

Over the past decade, the NSWP has produced a number of very visible and notable achievements. For example, the program has fundamentally changed how researchers approach the study of the Earth's space environment. Today, because of the efforts of the seven agencies in the program, the generation of space weather in the context of its effects on critical technologies is understood as the result of an integrated physical system in which all components from Sun to Earth interact. Hence, researchers increasingly tend to regard space weather and the Sun-Earth system in which it occurs as a whole, rather than as a diverse collection of parts.

This systems understanding, together with the need to be able to predict space weather events, has led to the development of NASA's Community Coordinated Modeling Center (CCMC). This center is a multiagency partnership to provide access to modern space science simulations and to support the transition to space weather operations of modern space research models.

As a second example, the NSWP stimulated the initiation of the technical journal/magazine *Space Weather: The International Journal of Research and Applications*. This Internet-distributed technical magazine (with a hardcopy *Quarterly* edition), published by the American Geophysical Union, contains peer-reviewed technical articles, plus shorter feature articles, news, commentary, and editorials (http://www.agu.org/journals/sw/).

The NSWP has engendered major efforts in the academic community to construct usable models for portions of the solar-terrestrial system, as well as for more inclusive Sun-to-Earth models. All these models have been designed to address user needs and concerns. The modeling activities are conducted in several major modeling centers supported by the DOD, NASA, and NSF.

The DOD has supported three Multidisciplinary University Research Initiatives (MURIs) that address important space weather modeling problems. The DOD has also supported the development of an undergraduate-level textbook on space weather.

NSF awarded one of its grants for a National Science and Technology Center (NSTC) to a multi-university, multi-institution activity devoted to creating a physics-based numerical simulation model that describes the space environment from the Sun to the Earth. This Center for Integrated Space Weather Modeling (CISM) involves several universities, government laboratories, and industry.

NASA has initiated the Living With a Star (LWS) program, a research program focused on space weather applications (http://lws.gsfc.nasa.gov/). The importance of space weather understanding, monitoring, and prediction has been heightened by the recent U.S. commitment to human exploration of the Moon and Mars. This exploration will expose astronauts and spacecraft to a hazardous space weather environment that will need to be better understood and predicted. The United States has made a good beginning in supporting NASA's ambitious Exploration Initiative, which owes much to the LWS program and the NSWP. However, the work thus far is only a start; much remains to be accomplished in understanding and predicting space weather conditions for human space travel.

Popular interest in the emerging discipline of space weather is on the rise. The NSF cosponsored development of an IMAX© movie production about the recent solar maximum (high point of the solar cycle). Two popular texts, articles in *National Geographic,* and the Internet-based outreach programs funded by NSF and NASA focus on educating the public about space weather and its origins in the Sun-Earth system. Congressional awareness of space weather increased when the Halloween solar storms of 2003 coincided with funding decisions for NOAA/SEC.

The requests for data and service products from the SEC have increased continually since the NSWP began, largely because of the growth in awareness of the SEC’s capabilities for space weather forecasts and services. Through the SEC’s Space Weather Week, held each spring in Boulder, Colorado, researchers, governmental and nongovernmental users of forecasts and services, and private sector vendors have the opportunity to interact and to develop new concepts for migration of space weather research into useful products and services. The interests of the space weather user community, as expressed at Space Weather Week, continue to expand. For example, a prominent user group with enhanced participation at the most recent Space Weather Week (April 2006) represented the civil space transport and tourism industry.

Despite these notable advances, the NSWP has also experienced some significant shortfalls and difficulties. Some data collection capabilities have declined or will decline in the near future. For example, if current plans hold, the United States will be flying fewer space weather sensors on future NOAA weather satellites than are currently being flown. This outcome will surely cause a sizeable decrease in capabilities to predict space weather events. Further, resources for the creation and implementation of improved operational forecasts (the so-called transition of research to operations) have declined in the past several years. The SEC has experienced resource instabilities that have hindered provision of national space weather services.

Finding 2.1. The First Decade. Since its inception in 1995, the National Space Weather Program (NSWP) has had a number of noteworthy achievements, most of which likely would not have been attained without the program's existence. Significant strides have been made toward institutionalizing forecast and protection mechanisms for safeguarding against space weather events that may impact many of the significant technology systems on which the United States depends for security, commerce, and advances in science. Despite many notable advances, significant shortfalls in the program also exist and are outlined in this report.

Recommendation 2.1.1. The highly successful National Space Weather Program should continue as an interagency program; however, it should be updated and modified as detailed in the further recommendations of this report.

National Oceanic and Atmospheric Administration

NOAA's Space Weather Program monitors, measures, and specifies the space environment and provides timely and accurate operational space weather forecasts, warnings, alerts, and data to end users in the United States and around the world. The end-to-end program develops space weather observational requirements for NOAA's space-based sensors, ingests and processes their (and others') data, performs research to understand the processes that cause severe space weather, transitions research into operations to improve services, archives data from NOAA and the DOD, and makes the archived data accessible to government and private users.

NOAA's Space Weather Program includes activities within the National Weather Service (NWS) and the National Environmental Satellite, Data, and Information Service (NESDIS). NWS activities are conducted through the Space Environment Center (SEC), which is part of the National Centers for Environmental Prediction (NCEP). NESDIS activities are conducted by the National Geophysical Data Center. These two centers, which are both located in Boulder, Colorado, are direct components of the Space Weather Program. In addition, NOAA's Office of Marine and Aviation Operations provides staff support, and the National Geodetic Survey, within NOAA's National Ocean Service, provides data, as does the Satellite Services Program within NESDIS.

The United States Air Force is an especially strong partner, providing services and data, as well as detailing staff to the SEC. NASA provides key science data from its research satellites and plans to provide science data from future approved missions. The U.S. Geological Survey (USGS) provides key ground-based data. The Space Weather Program also receives data from many countries and their space agencies throughout the world. NOAA is also the lead partner in the International Space Environment Service (ISES), the body responsible under the International Council for Science (ICSU) for coordinating the worldwide provision of space weather services.

National Aeronautics and Space Administration

Science both enables exploration and is enabled by it. A NASA goal in the era of the Vision for Space Exploration is to develop a balanced program of space science within the Science Mission Directorate. The Heliophysics Division in the Science Mission Directorate is organized to address three broad science objectives:

Opening the Frontier to Space Environment Prediction. Investigate and communicate the fundamental physical processes of the space environment—from the Sun to Earth, to other planets, and beyond to the interstellar medium.

Understanding the Nature of Our Home in Space. Discover and document how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields.

Safeguarding the Journey of Exploration. Using new scientific insight, maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space.

To achieve these goals the Heliophysics Division organizes and executes scientific space flight missions to investigate physical conditions and processes found in the solar system. It also conducts programs of theory and research to support these missions through development of new theories and numerical models, creation of national-class databases for conservation of data and scientific results, support for development of new scientific assets such as an extended mission fleet and a guest investigation program, and the training and support of the next generation of explorers.

Where possible, NASA's research and analysis mission is extended to the utilization of new knowledge for societal benefit by forming partnerships with industry, academia, and other governmental agencies that are also engaged in the development of the emerging field of space weather research and predictive capability.

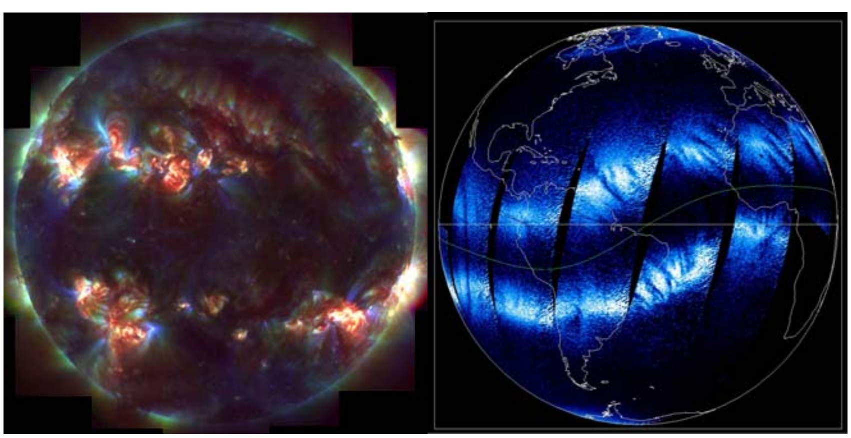

Figure 2-2. The Sun and the Earth observed from space.

Department of Defense

The DOD supports the National Space Weather Program primarily in three areas of strategic priority: forecasting and specification, observation, and technology transition and integration.

The DOD's primary space weather concern is the state of the ionosphere as it impacts communications, navigation, and targeting operations. The U.S. Air Force is responsible for providing space environmental services to all of DOD. The Air Force Weather Agency (AFWA) reports solar activity and conducts forecasting of the ionosphere and magnetosphere, working in close coordination with NOAA/SEC.

The DOD provides reliable, ground-based and on-orbit space environmental observations to the community. DOD solar observatories in Hawaii, New Mexico, Massachusetts, Italy, and Australia detect and report optical flares and their radio signatures on discrete VHF, UHF, and SHF frequencies and from coronal plasma movements. The DOD characterizes the lower portion of the ionosphere by maintaining two dozen ionospheric sounders around the world. It captures the upper portion of the ionosphere with in situ and remote sensing instruments carried on satellites of the Defense Meteorological Satellite Program (DMSP).

Both AFWA and the Air Force Space Command (AFSPC) facilitate technology transition and integration. AFWA implements models for operational use, most notably the Global Assimilation of Ionospheric Measurements (GAIM) model starting in 2006. AFSPC integrates space environmental forecasts directly into joint operations at the Joint Space Operations Center. AFSPC is also developing a system to directly integrate space environmental information into combatant commanders' command and control systems.

Additionally, the DOD conducts research related to space weather and develops sensors and systems through the Air Force Research Laboratory, the Naval Research Laboratory, and the Air Force Office of Scientific Research.

National Science Foundation

Currently, the NSF supports about $2 million annually in focused space weather research grants. It also supports related space physics research programs in aeronomy, magnetospheric physics, and solar-terrestrial physics. Special NSF research programs within these broad space physics programs include: Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR); Geospace Environment Modeling (GEM); Radiative Inputs of the Sun to Earth (RISE); and Solar and Heliospheric Interplanetary Environment (SHINE). The NSF currently supports a number of space weather modeling programs, including the Center for Integrated Space Weather Modeling (CISM), a National Science and Technology Center established in 2002.

In addition to the basic research programs, NSF supports a variety of ground-based observing instruments and major facilities of relevance to the NSWP. Facilities include a chain of incoherent scatter radars located in Jicamarca, Peru; Arecibo, Puerto Rico; Millstone Hill, Massachusetts; and Sondre Stromfjord, Greenland. NSF also supports the U.S. component of the Super Dual Auroral Radar Network (SuperDARN). Also important to space weather is the NSF support of the National Solar Observatory and the National Center for Atmospheric Research (NCAR), including the High Altitude Observatory. NSF also supports relevant space weather research using instrumentation installed in the Antarctic and Arctic regions.

The latest space weather facility, the Advanced Modular Incoherent Scatter Radar (AMISR), is currently under construction in Fairbanks, Alaska. Using state of the art technology, AMISR sets a new world standard in upper atmospheric research facilities, and its unique design features allow the radar to be disassembled and moved as scientific needs dictate.

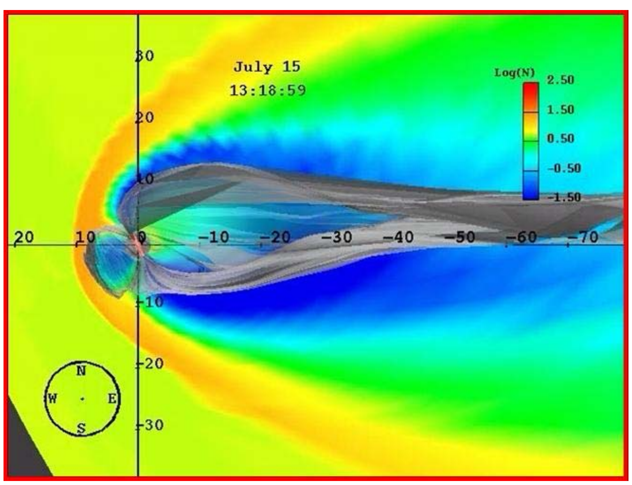

Figure 2-3. Computer simulation of Earth's magnetosphere.
This illustration of an early magnetospheric model developed by CISM is tightly coupled to a realistic model for the polar ionospheres and is driven by solar wind plasma and magnetic field data forward of the calculation domain. Although lacking important physical processes in both the magnetosphere and ionosphere, this is the simplest possible self-consistent model based on first-principle representations.

Department of the Interior Geomagnetism Program

The Geomagnetism Program of the Department of the Interior's U.S. Geological Survey (USGS) serves the NSWP by providing high-quality, ground-based magnetometer data over a wide range of timescales from 14 observatories distributed across the United States and its territories. The Geomagnetism Program collects, transports, and can disseminate these data in near-real time. The Geomagnetism Program also has significant data-processing and data-management capacities. The USGS Geomagnetism Program's data services form the basis of many space-weather diagnostics used by NOAA/SEC, AFWA, other scientific agencies, and the nongovernmental sector.

On an international scale, working through the Intermagnet organization and with other national geomagnetism programs, the USGS Geomagnetism Program assists in coordinated international monitoring of the Earth's magnetic field.

The program has a small research element which concentrates on the analysis of ground-based magnetic observatory data. Additional information can be found at:
http://geomag.usgs.gov and http://www.intermagnet.org

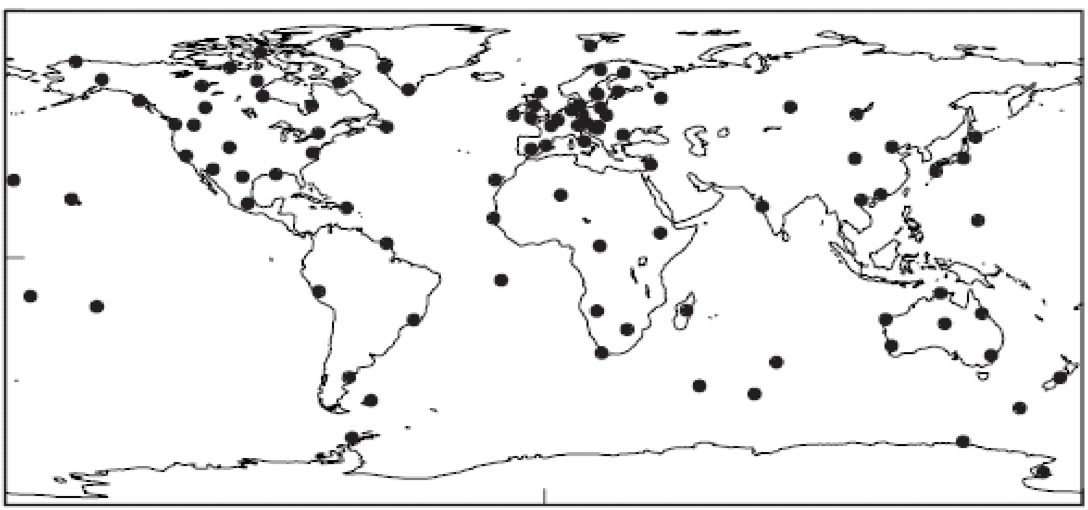

Figure 2-4. World map of locations of Intermagnet observatories.